data, degradation was estimated using fuzzy inference. In this experiment, six kinds of kinetic viscosity (a:16.88 kg/L, b:16.94 kg/L, c:16.96 kg/L, d:17.10 kg/L, e:17.47 kg/L, f:17.59 kg/L) of insulating oils were used. Center frequencies of probes were 2.25 MHz and 5 MHz, respectively. Correlation coefficients between inference and practical kinetic viscosity were 0.7834 (2.25 MHz) and 0.7890 (5 MHz), respectively. Consequently, experimental results show that this method could evaluate degradation of insulating oil indirectly. It reminds as a future work to analysis other parameters (e.g. density).

Session: 5I

THIN FILMS AND DEVICES
Chair: J. Kosinski
U.S. Army RDE Command

5I-1 10:30 a.m.

SAW ANALYSIS OF THE MG\textsubscript{x}ZN\textsubscript{1−x}O/SIO\textsubscript{2}/SI SYSTEM

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Magnesium zinc oxide (Mg\textsubscript{x}Zn\textsubscript{1−x}O) is a new piezoelectric material formed by alloying ZnO and MgO. In this study, the SAW velocity dispersion and electromechanical coupling coefficients (K\textsuperscript{2}) in the Mg\textsubscript{x}Zn\textsubscript{1−x}O (x=0-30%)/SiO\textsubscript{2}/Si system is analyzed using the transfer matrix method. Si is chosen as the substrate for potential integration of SAW device with the main stream integrated circuits technology. The use of different Mg content in Mg\textsubscript{x}Zn\textsubscript{1−x}O films leads to change in piezoelectric properties. The SAW characteristics of the system can be further tailored by varying the thickness ratio between the Mg\textsubscript{x}Zn\textsubscript{1−x}O and SiO\textsubscript{2} layers. The SiO\textsubscript{2} layer benefits the temperature compensation, as it possesses a negative temperature coefficient of delay (TCD), while the Mg\textsubscript{x}Zn\textsubscript{1−x}O layer and the Si substrate have positive TCDs. The effect of different Mg\textsubscript{x}Zn\textsubscript{1−x}O to SiO\textsubscript{2} thickness ratios on SAW propagation in the multilayer structure is investigated. Four multilayer SAW device configurations, including IDT/ Mg\textsubscript{x}Zn\textsubscript{1−x}O/SiO\textsubscript{2}/Si, Mg\textsubscript{x}Zn\textsubscript{1−x}O/IDT/SiO\textsubscript{2}/Si, IDT/ Mg\textsubscript{x}Zn\textsubscript{1−x}O/metal ground plane/SiO\textsubscript{2}/Si, and metal ground plane/Mg\textsubscript{x}Zn\textsubscript{1−x}O/IDT/SiO\textsubscript{2}/Si, are studied. It is found that at the high frequency range, with each 10% increase of the Mg content in the Mg\textsubscript{x}Zn\textsubscript{1−x}O, SAW velocity increases by 5.8%, whereas K\textsuperscript{2} decreases by around 30%. At Mg\textsubscript{x}Zn\textsubscript{1−x}O thickness-frequency products hf larger than 1600, the SAW energy for the base wave mode is trapped in the Mg\textsubscript{x}Zn\textsubscript{1−x}O layer and the thickness of SiO\textsubscript{2} no longer affects the SAW propagation. The multilayer configurations also play an important role. It is found that the Mg\textsubscript{x}Zn\textsubscript{1−x}O/IDT/SiO\textsubscript{2}/Si configuration yields the highest coupling coefficient K\textsuperscript{2}=4.2% at hf=1080 with ZnO: SiO\textsubscript{2}=2:1, while the IDT/ Mg\textsubscript{x}Zn\textsubscript{1−x}O/SiO\textsubscript{2}/Si configuration yields the highest SAW velocity. The current study indicates that using Mg\textsubscript{x}Zn\textsubscript{1−x}O-based
Multilayer structures will provide flexibility in SAW device design as well as the ability to tailor SAW properties. 

This work has been partially supported by the National Science Foundation under the grants ECS-0088549

5I-2 10:45 a.m.

IMPROVEMENTS IN THE TEMPERATURE STABILITY OF A IDT/ZNO/FUSED QUARTZ THIN FILM SAW DEVICE WITH ZNO OVER LAYER

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Piezoelectric thin film layered structures allow the fabrication of integrated SAW devices on silicon or glass substrates for producing low cost devices that can be mass produced. Amongst the various piezoelectric thin film materials (LiNbO₃, PZT, LiTaO₃ etc.), ZnO films can be grown reproducibly over a wide range of thickness (upto 20 micron) by rf/dc magnetron sputtering techniques. In the case of ZnO films, fused quartz, which is the purest form of SiO₂, is found to be a convenient substrate because its material parameters are available and SAW propagation characteristics of the ZnO/fused quartz structure can be studied. ZnO possesses a positive temperature coefficient of delay (TCD) of 30 ppm/°C and it is of interest to fabricate a zero TCD device. Especially for low frequency applications (< 70 MHz) sufficiently thick ZnO films are required on negative TCD glass substrates (-91 ppm/°C) to effectively offset the TCD to zero. When film thickness is not sufficient the overall TCD of the layered structure remains negative and the need for an additional over layer with positive TCD becomes necessary for temperature compensation. In the present work, usefulness of a ZnO over layer, which has a positive TCD has been explored for fabricating a temperature stable thin film SAW device.

Intermediate frequency SAW filters operating at different frequencies (38, 41, 60, 63 and 64 MHz) have been fabricated using thick ZnO films (8 to 14 micron thickness) on fused quartz substrates. SAW propagation characteristics of the fabricated device such as electromechanical coupling coefficient (K₂), SAW phase velocity (v), insertion loss and TCD have been measured. The influence of a ZnO over layer is specifically studied on a 63 MHz device, which initially exhibited a low insertion loss of 21 dB and a TCD of # 31 ppm/°C. SAW propagation characteristics of the device were measured as a function of increasing ZnO over layer thickness. A 5.4 micron thick ZnO over layer has been found to reduce the TCD of the IDT/ZnO/fused quartz layered structure to almost zero (#3 ppm/°C) and a coupling coefficient, K² = 1.1 % and insertion loss, IL = 27 dB were measured.

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ALN EPITAXIAL FILM ON 6H-SIC(0001) USING MOCVD FOR GHZ-BAND SAW DEVICES

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We have developed aluminum nitride (AlN) (0001) epitaxial film with crack free surface on 6H-silicon carbide (6H-SiC) (0001) substrate using metal-organic-chemical-vapor deposition (MOCVD) method without hydro chloride (HCl) annealing. Crack free surface of AlN leads decreasing the propagation loss and stable fabrication of interdigital transducer (IDT) strip lines. Since 6H-SiC substrate features higher stiffness than sapphire substrate, the SAW velocity in AlN/6H-SiC structure is expected to be more than that of AlN/Al2O3 structure. AlN/6H-SiC structure has potential to be useful for GHz-band SAW devices for application of wireless communication. A lattice mismatch between AlN and 6H-SiC is 1.1%. AlN and 6H-SiC are suitable combination. The surface of 6H-SiC substrate has a lot of scratches and defects. The scratches and defects make many cracks on the surface of AlN. The cracks on AlN surface lead increasing propagation loss and breaking down of IDT strip lines. The scratches and defects are usually removed using HCl annealing with the temperature of over 1,300 degrees C. Because HCl gas erodes CVD equipment, crack free AlN growth process without HCl annealing is strongly required. In this work, in order to deposit crack free AlN film without HCl annealing, we have applied 3-D growth condition. 3-D growth condition is usually used for buffer layer in hetero epitaxisy. The conditions were substrate temperature of 1,100 degrees C and V-III mol ratio of 25,000. The pressure in reactor was 20 torr. AlN deposited with these conditions was proved to be c-oriented single crystal by x-ray diffraction (XRD) and pole figure measurement. It is noticed that there was crack free surface of AlN obtained using scanning electron microscope (SEM). Mean roughness measured by atomic force microscope (AFM) of surface of AlN was 1.5 nm, which was equal to height of 1-unit-cell 6H-SiC. It is confirmed that the surface of deposited AlN has sufficiently flatness to fabricate GHz-band SAW devices. In conclusion, we have developed AlN (0001) epitaxial film with crack free surface on 6H-SiC (0001) substrate using MOCVD method without HCl annealing. AlN (0001)/6H-SiC(0001) structure has potential of GHz-band SAW devices.

PREPARATION OF ALN THIN FILM ON FREE STANDING DIAMOND FILM BY ION BEAM SPUTTER


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Chemical vapor deposition (CVD) diamond is an attracting material because of excellent physical and chemical properties, particularly in the highest surface acoustic wave (SAW) velocity. High frequency SAW devices could be made by coupling CVD diamond film with suitable high quality piezoelectric thin film such as aluminum nitride (AlN). CVD Diamond film results in the large roughness surface, therefore smooth surface becomes an important issue. Without many complicated processes to smooth the surface, free-standing diamond film (FSDF) with surface roughness less than 26 nm (Figure 1.) on the bottom side can be used as a substrate for SAW device. Since the phase velocity of AlN is the highest (6700m/s) among the known piezoelectric materials such as ZnO (5700m/s). Highly C-axis oriented AlN thin film deposited on FSDF is necessary for high performance SAW device. In order to deposit high quality AlN thin film, ion beam sputtering is used in different N2/Ar ratios under different substrate temperatures. The surface morphology and quality were obtained by X-ray diffraction analysis (XRD), scanning electron microscope (SEM), and atomic force microscope (AFM). The resistance of the film is determined by four point probe. Consequently, highly oriented AlN thin film with extremely low Ra from 26nm to 8nm on FSDF was obtained by ion beam sputter with denser and smoother film surface than conventional RF sputter.

5I-5 11:30 a.m.

SURFACE ACOUSTIC WAVES IN ZNO/AL$_X$GA$_{1-X}$N/C-SAPPHIRE STRUCTURES

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Piezoelectric AlN thin films deposited on (0001) C-plane sapphire substrates are attractive for low-loss and high frequency SAW devices. However, growth of epitaxial quality AlN films is difficult due to its low deposition rate and high growth temperatures. On the other hand, ZnO is a promising piezoelectric material with high electromechanical coupling coefficients; furthermore, high quality epitaxial ZnO films can be grown at temperatures hundreds of degrees lower than AlN. By depositing piezoelectric ZnO and Al$_x$Ga$_{1-x}$N multilayer structures on C-plane sapphire substrates, large coupling coefficient $k^2$ and high phase velocity can be obtained. In this work, the SAW velocity and coupling coefficients of the ZnO/Al$_x$Ga$_{1-x}$N (0≤x≤1)/C-Al$_2$O$_3$ multilayer systems are evaluated as a function of the Al mole percentage, x in Al$_x$Ga$_{1-x}$N, and of the thickness ratio $(h_1/h_2)$ of ZnO $(h_1)$ to Al$_x$Ga$_{1-x}$N $(h_2)$. It has been found that when the thickness ratio $h_1/h_2$ is unity, a wide thickness-frequency product $(hf)$ region where coupling is close to its maximum value $k^2_{\text{max}}$, is obtained. The $k^2_{\text{max}}$ of the Sezawa wave mode $(h_1 = h_2)$ is estimated to be 4.81% for ZnO/GaN, and 4.56% for ZnO/AlN. The bandwidth, in which the coupling coefficient is within ±0.3% of $k^2_{\text{max}}$, is calculated to be 3390 hf for ZnO/AlN, and 720 hf for ZnO/GaN, respectively. Thus, the hf region where the coupling coefficient is
close to the maximum value broadens with increasing Al content, while \( k_{\text{max}}^2 \) decreases slightly. ZnO/Al\(_{x}\)Ga\(_{1-x}\)N multilayer structures are epitaxially grown on C-plane sapphire substrates by MOCVD. SAW devices are fabricated and tested. The theoretical and experimental results are found to be well matched.

This work has been partially supported by the National Science Foundation under the grants ECS-0088549 and ECS-0224166.

5I-6 11:45 a.m.

TEMPERATURE CHARACTERISTIC OF ALN THIN FILM ON Y-64° LiNbO\(_3\) COMPOSITE SUBSTRATE

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LiNbO\(_3\) is used extensively for the SAW devices in which the LSAW Y-64° LiNbO\(_3\) is used mainly in the RF filter area based on its excellent properties, such as large piezoelectric coupling constant (11.3%), high SAW velocity (4742m/s), but the poor temperature stability (TCD = -70 ppm/J) is the main drawback of this substrate material. AlN thin film is an attractive material that has some excellent characteristics, such as high SAW velocity (>15600 m/s), piezoelectricity, stable chemical properties and high temperature stability with positive temperature coefficient. C-axis-oriented AlN films were deposited on the Y-64° LiNbO\(_3\) by the rf magnetron sputtering in this research to form a composite substrate with more better temperature stability.

The crystalline structures of the films were determined by X-ray diffraction (XRD) and the thickness of films is measured by the surface profilometer. The standard interdigital transducer (IDT) was fabricated on the surface of the substrate. The frequency response and the input impedance of the circuit were measured by a network analyzer. The SAW properties were investigated from the experimental data.

The experimental results exhibited the high c-axis-oriented AlN thin films were successfully prepared on Y-64° LiNbO\(_3\), and the AlN thin films on Y-64° LiNbO\(_3\) reduce the large TCD(-70 ppm/J) of Y-64° LiNbO\(_3\) substrate. Three kinds of AlN thickness were used to compensate negative TCD of LiNbO\(_3\). TCD of the composite substrate will be largely reduced when the thickness of AlN thin films increases. Composite substrate (AlN thin films on Y-64° LiNbO\(_3\)) with small TCD (around -25 ppm/J) was fabricated with the film thickness about 4.5gm.